Human-induced global ocean warming on multi-decadal timescales

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PCMDI
Program for Climate Model Diagnosis and Intercomparison

CAPT
Cloud-Associated Parameterizations Testbed

ESGF
Earth System Grid Federation

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Experts from the leading observational groups:

NOAA/NODC

CSIRO (Australia)

Japan Agency for Marine-Earth Science and Technology (Japan)

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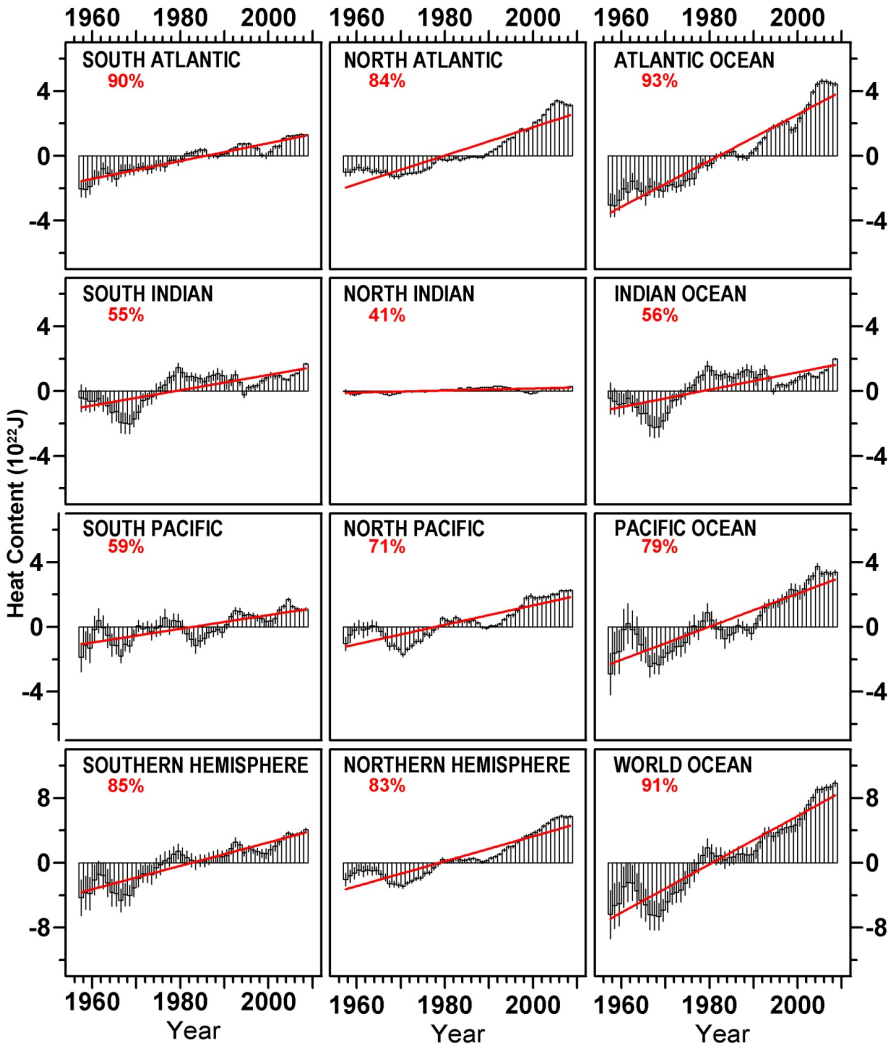
Presentation Outline

- Introduction
  - Evidence of global ocean warming
  - Previous ocean warming Detection and Attribution (D&A) studies
  - Why does this issue warrant further study?
- Observations and models used in this work
- Simulated and observed variability and trend comparisons
- Our D&A analysis and conclusions
- Plans to further advance our understanding of ocean warming

Observational evidence of global ocean warming



Numbers in red are % variance accounted for by this trend

Most recent estimates, Levitus et al. 2012 (GRL)

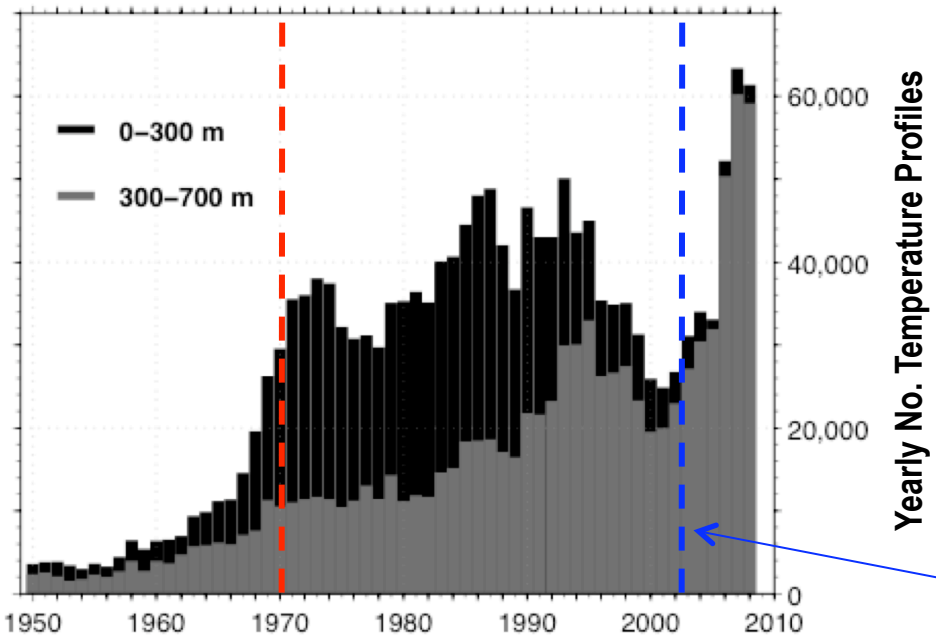
Analysis of the World Ocean Database

~ 8 million temperature profiles (0-700 m) used to compute Ocean Heat Content (OHC)

Coherent warming across all major basins

Multiple updates/corrections since first evidence (Levitus et al., 2000, *Science*)

Observing systems and sampling



Based on measurements from bottles, Expendable Bathythermograph **(XBTs)**, low- and high-resolution Conductivity, Temperature, and Depth profilers (CTDs), and most recently Argo floats

ARGO floats providing near global coverage

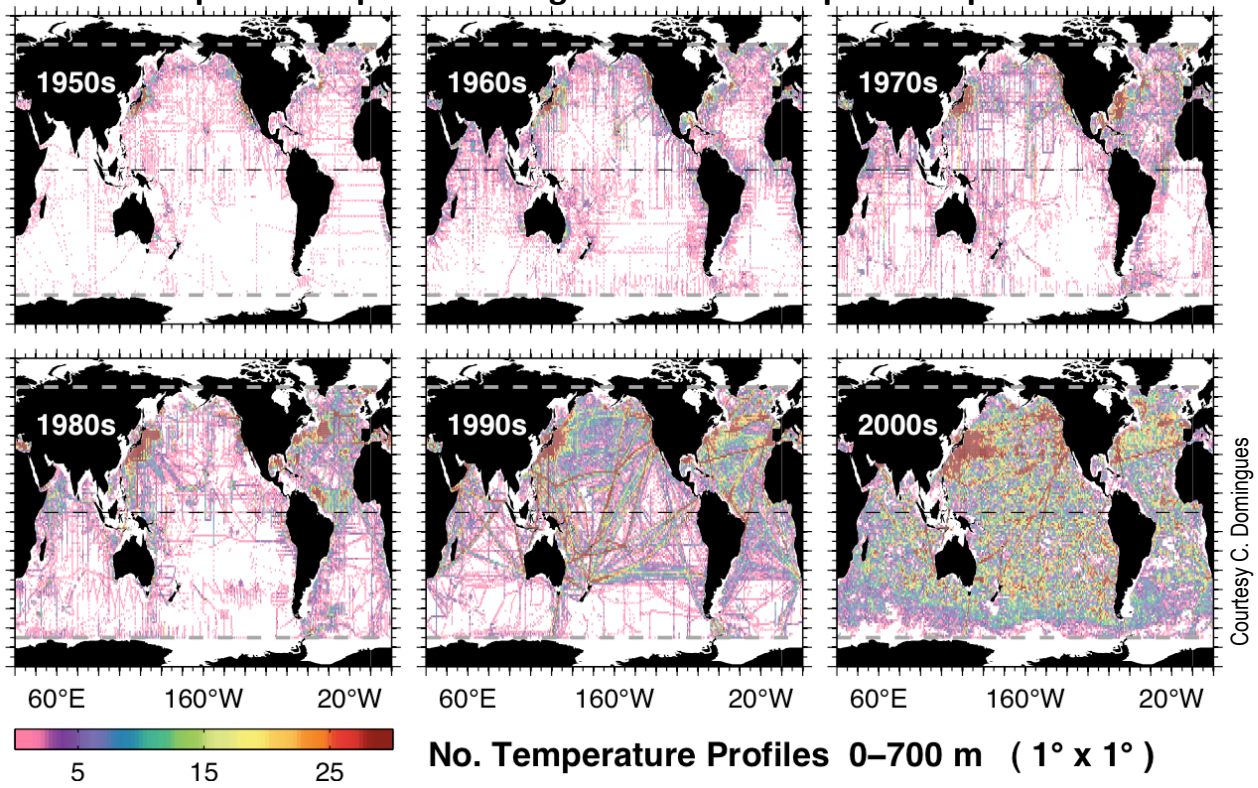
XBT's begin to be widely used

Measurement sampling history and "infilling"

Infilled temperature estimates

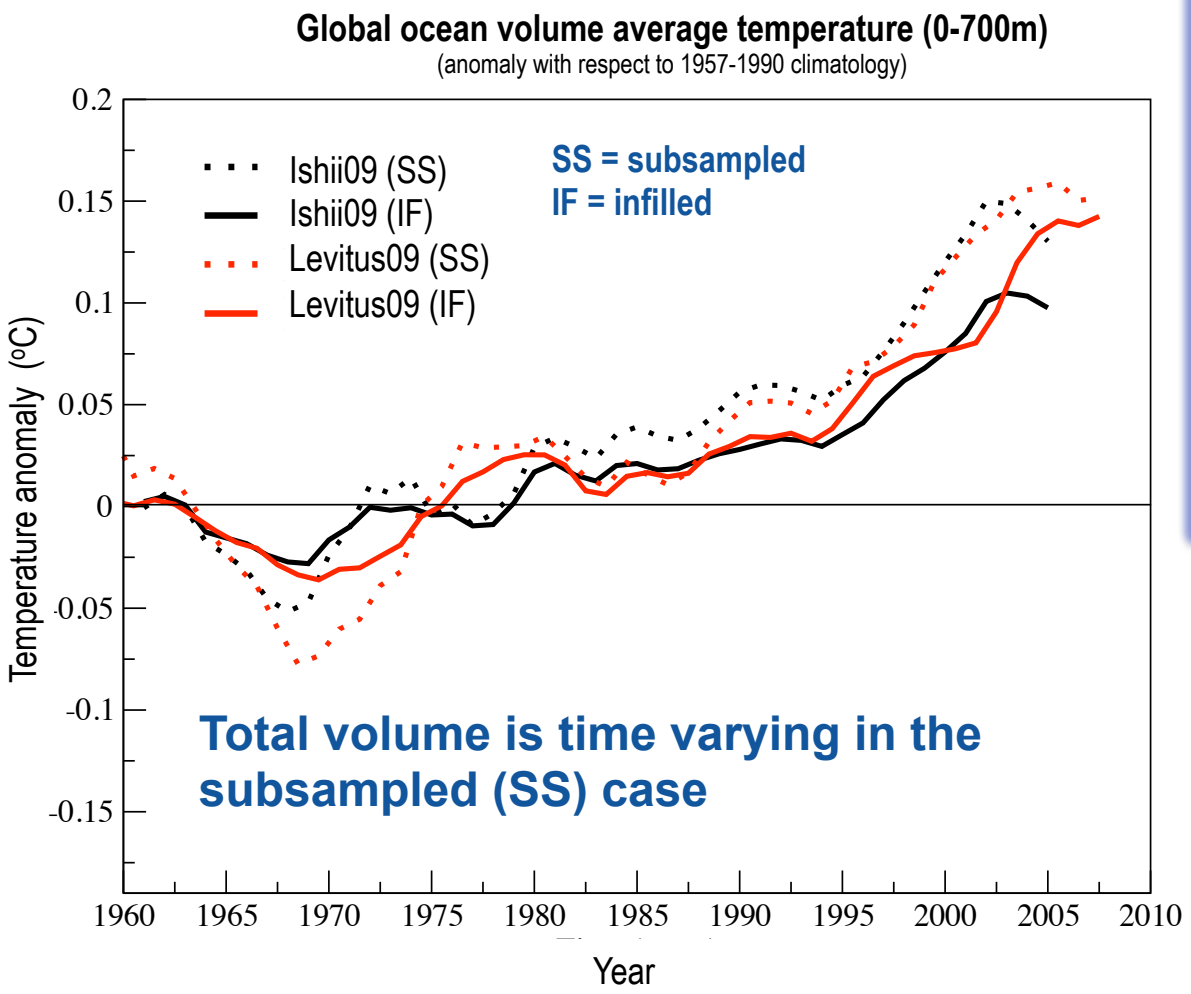
Domingues08: C. Domingues, J. Church, N. White, P. Gleckler, S. Wijffels, P. Barker, 2008 (*Nature*)
Levitus09: S. Levitus, et al., 2009 (*GRL*)
Ishii09: M. Ishii and M. Kimoto, 2009 (*J. Oceanography*)

Spatial-temporal coverage of 0-700m temperature profiles



A key difference between **Domingues08, Levitus09, Ishii09** is how they "infill" in areas where there are no measurements

Addressing sampling uncertainties



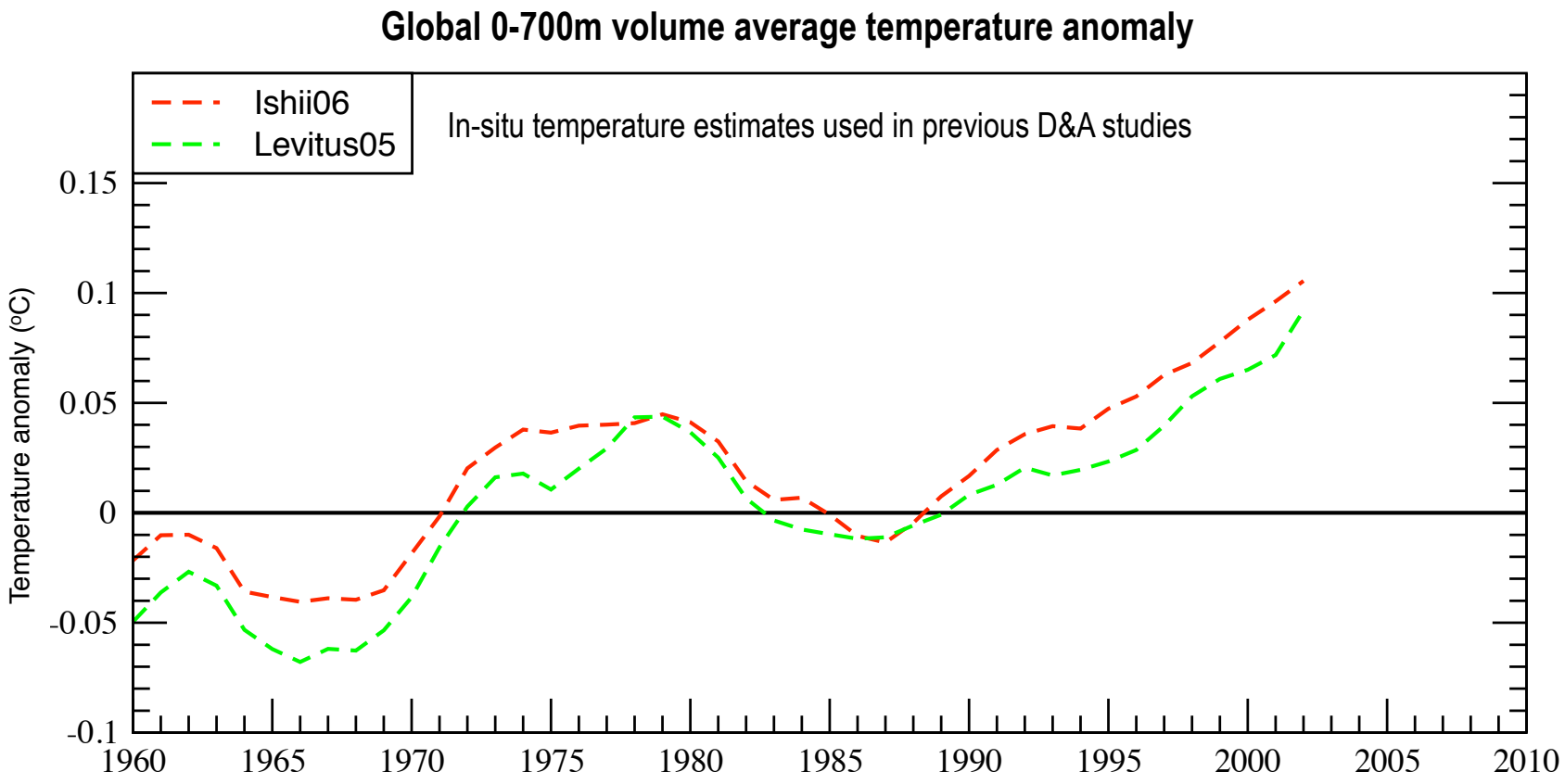
Why use
Volume Average Temperature (ΔT)
instead of
Ocean Heat Content (OHC)?

- Enables a fair comparison: sampling models consistently with historical measurements
- Circumvent use of "infilled" data

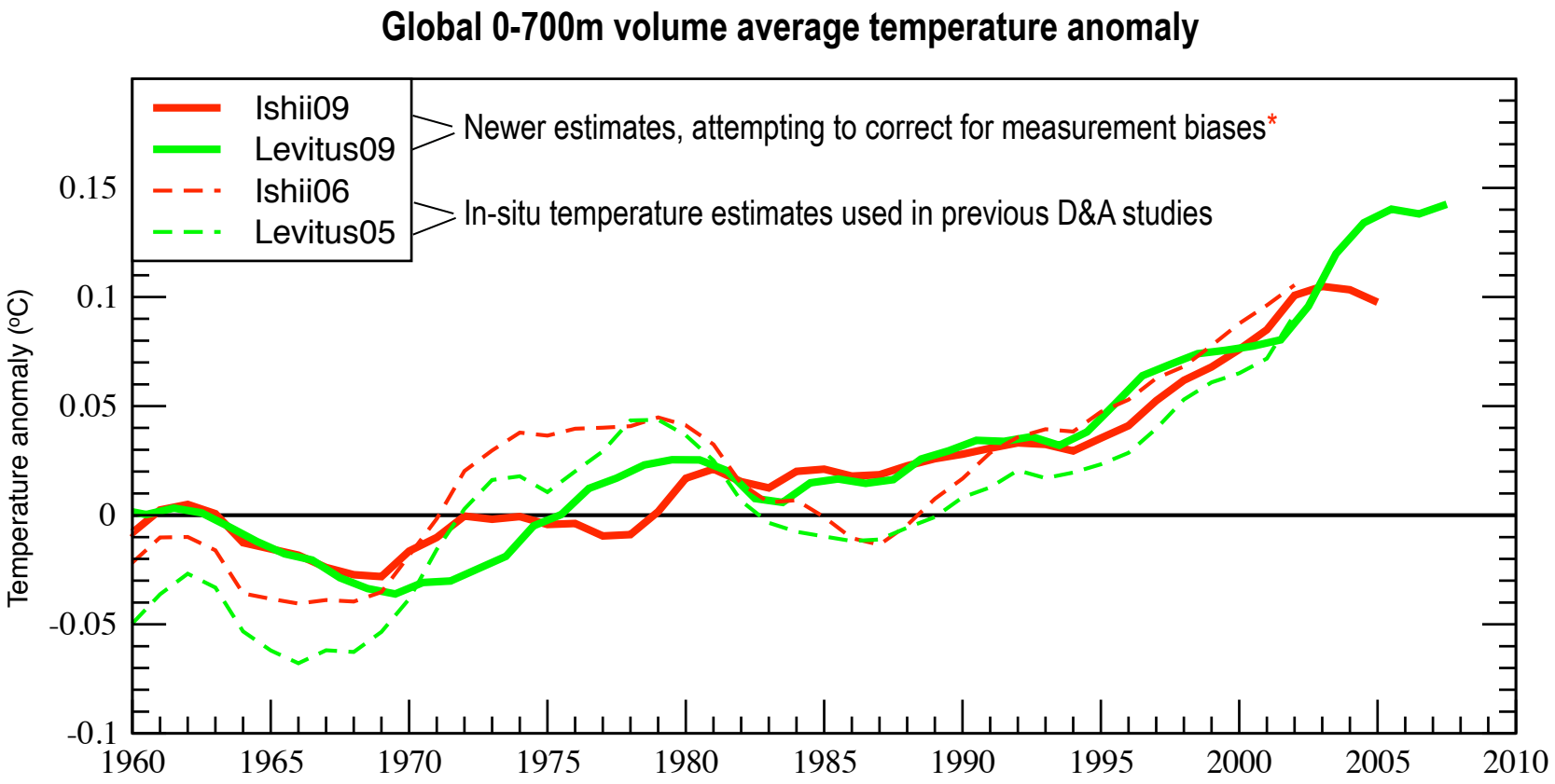
Both trends and variability appear larger with subsampled data

Older observationally-based records of in-situ temperature

Spatially-complete case

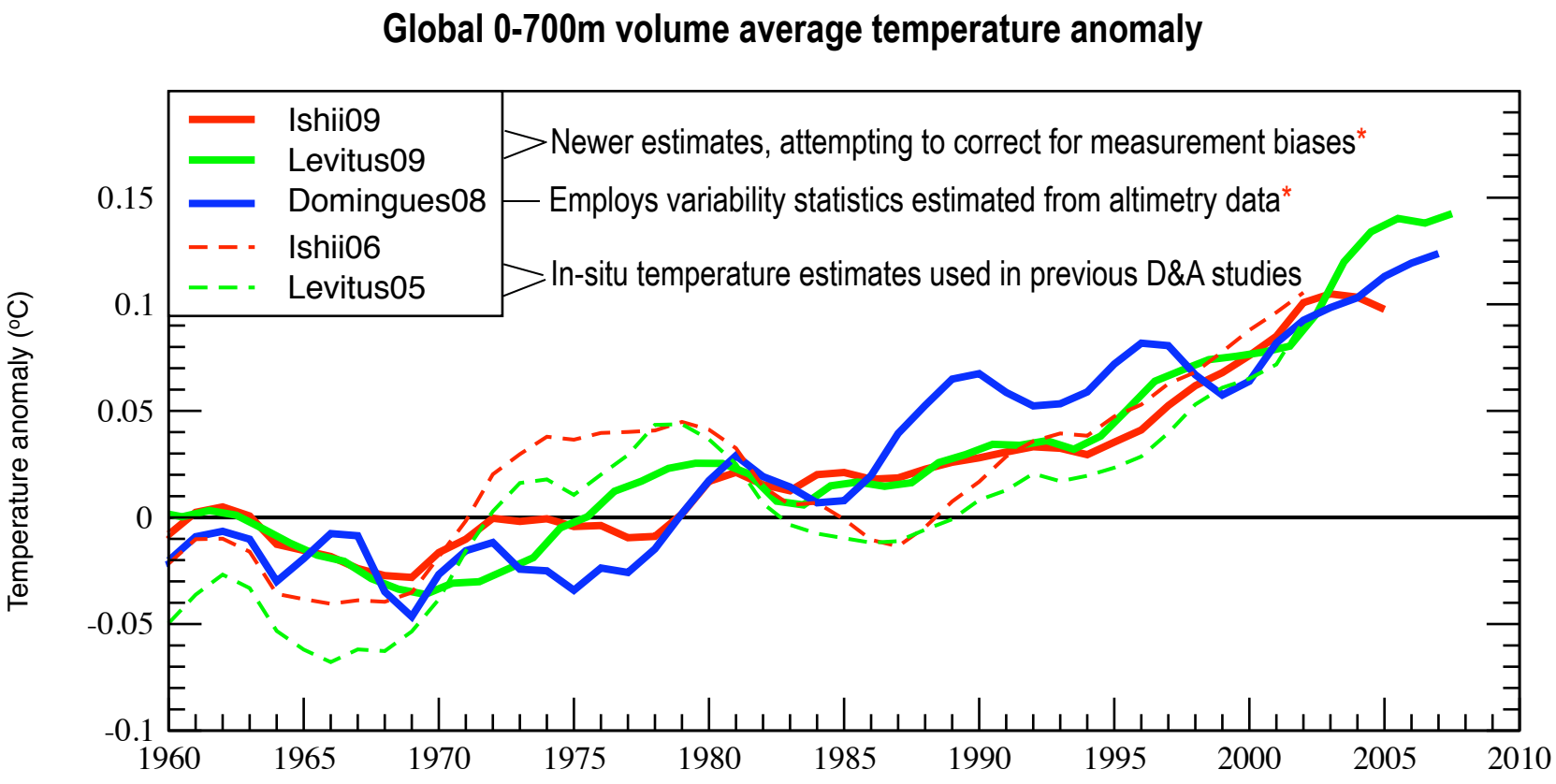


Improved observationally-based records of in-situ temperature



* Expendable Bathythermograph (XBT) "fall-rate" measurement biases identified by Gouretski and Koltermann (2007)

Improved observationally-based records of in-situ temperature



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Motivation for an in-depth ocean warming D&A analysis

- Approximately 90% of the heat trapped in the climate system associated with anthropogenicaly-induced global warming is in the oceans and is responsible for thermosteric sea level changes

- Improved observationally-based estimates of temperature changes (correcting for XBT biases)
  - Previous ocean warming D&A studies used older, uncorrected temperature data (e.g., Barnett et al., 2001 and 2005)

- Application of a multi-model D&A approach
  - Previous studies used only one or two models (e.g., Barnett et al., 2001 and 2005, Palmer et al., 2010)

- Evaluate the impact of factors known to be important for OHC D&A
  - Sampling deficiencies
  - Simulation "drift"
  - External forcing uncertainties
  - Estimates of longer time scale variability

Model results used in this study

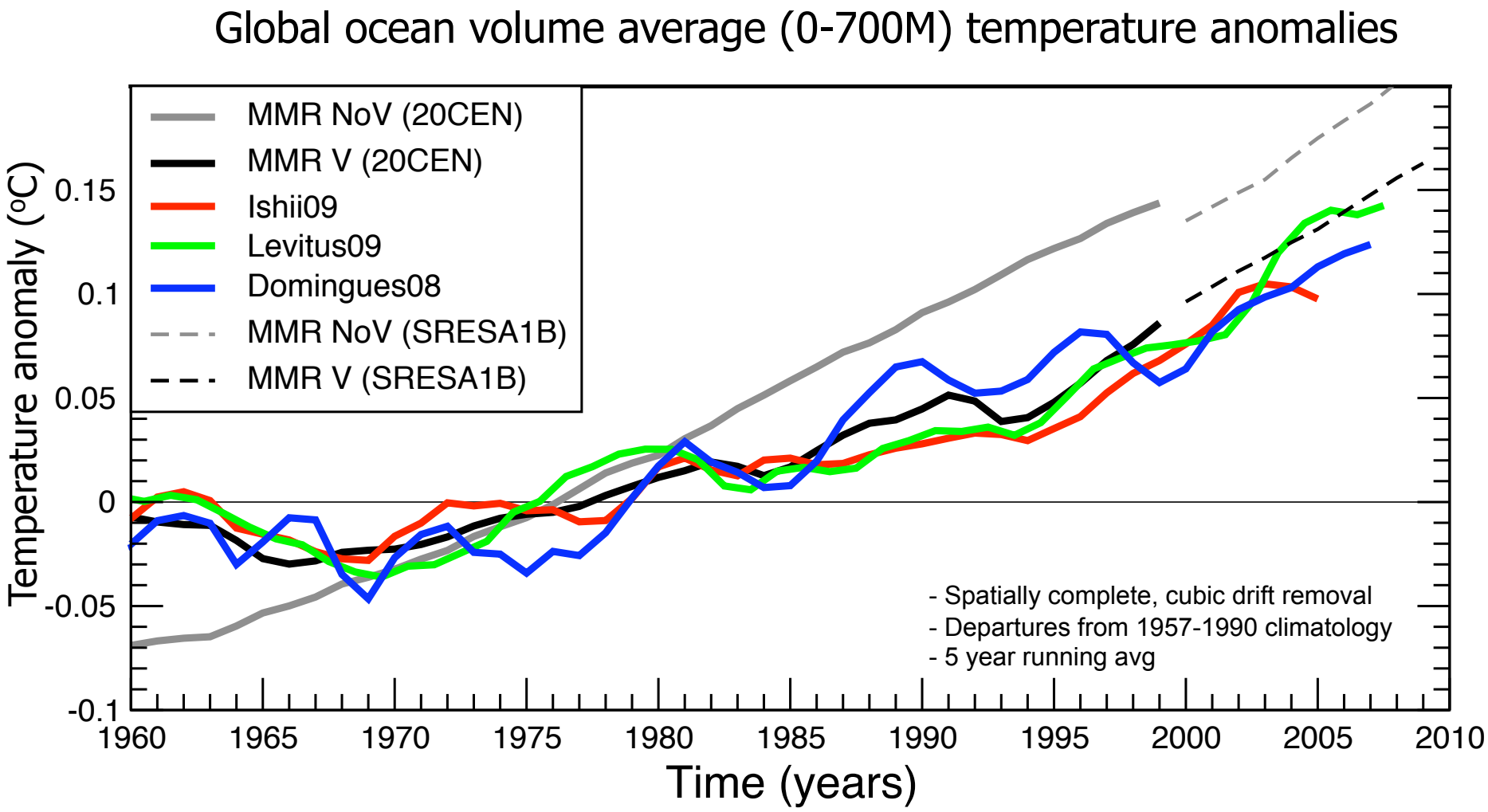
Simulations from CMIP3

(with necessary ocean model output)

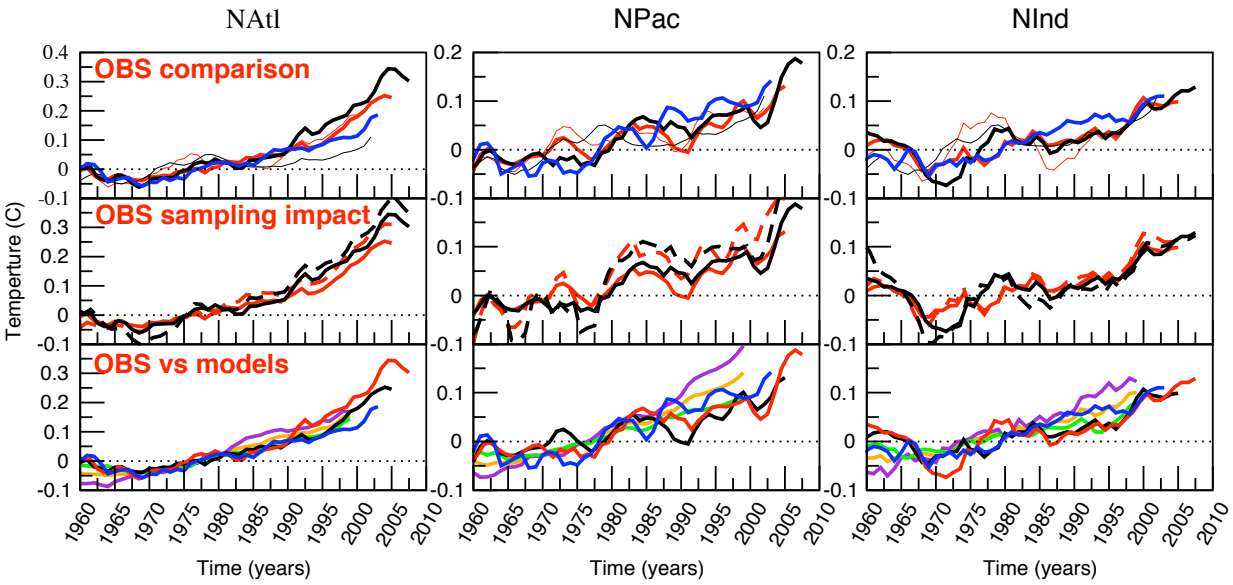
Model	Well-mixed GHGs	Volcanic aerosols	20Cen Runs
CCCma-CGCM3.1 (T47)	Y	NoV	5
NCAR CCSM3	Y	V	6
CNRM-CM3	Y	NoV	1
CSIRO-Mk3.0	Y	NoV	3
FGOALS-g1.0	Y	NoV	3
GFDL-CM2.0	Y	V	1
GISS-AOM	Y	NoV	2
GISS-EH	Y	V	4
GISS-ER	Y	V	7
MIROC3.2(medres)	Y	V	1
MIROC3.2(hires)	Y	V	3
MRI-CGCM2.3.2	Y	V	5
UKMO-HadCM3	Y	NoV	1

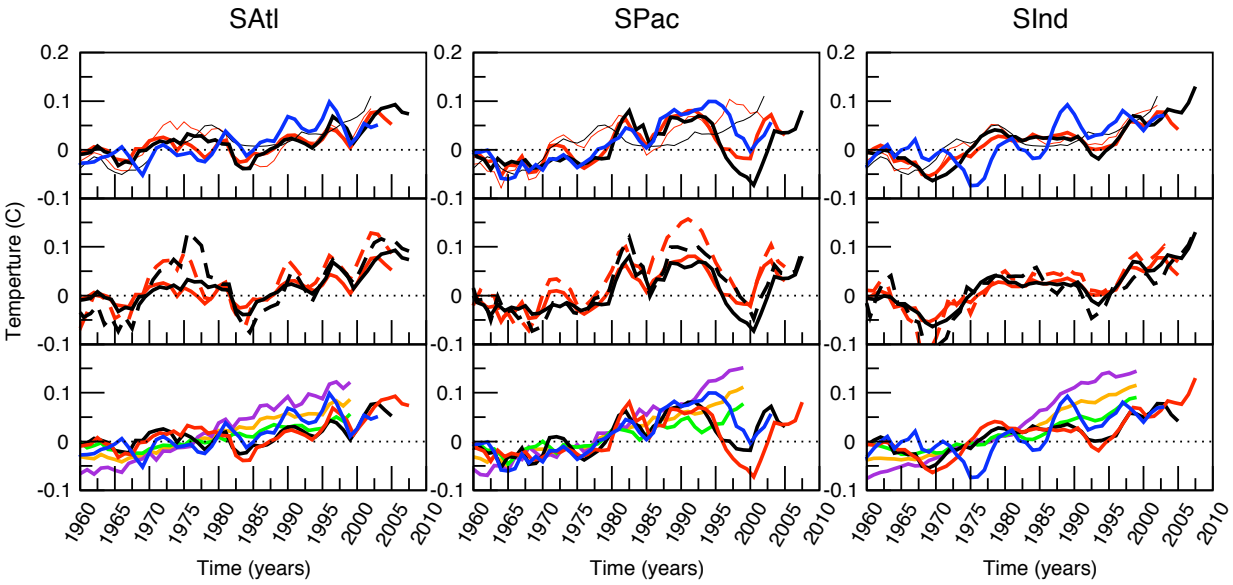
7 models with volcanic eruptions (V), 6 without (NoV)

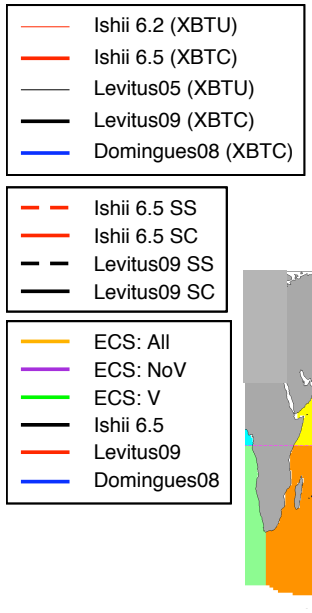
CMIP3 Multi-Model Response (MMR) vs. observations

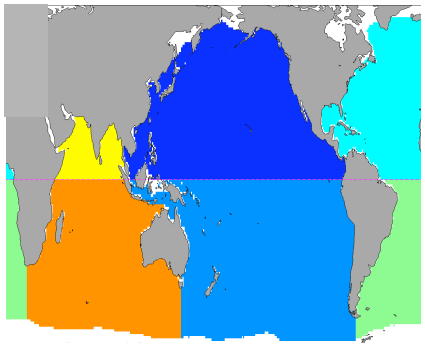


Our analysis is basin scale





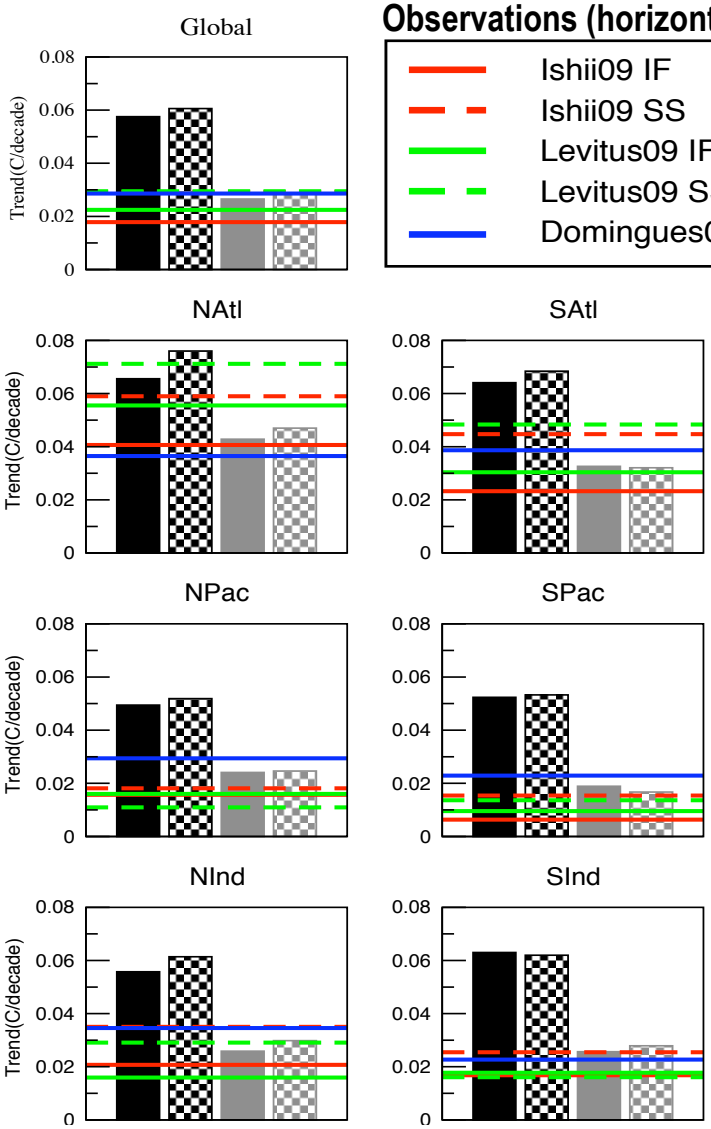




Basins definitions in this study

We aim to search for a time-increasing correspondence between a model-predicted basin scale ocean-warming “fingerprint” and observations, and then to determine whether such correspondence could be due to natural variability alone

Basin scale trends (1960-1999): Observed and simulated



Observations (horizontal lines)

- Ishii09 IF
- Ishii09 SS
- Levitus09 IF
- Levitus09 SS
- Domingues08 IF

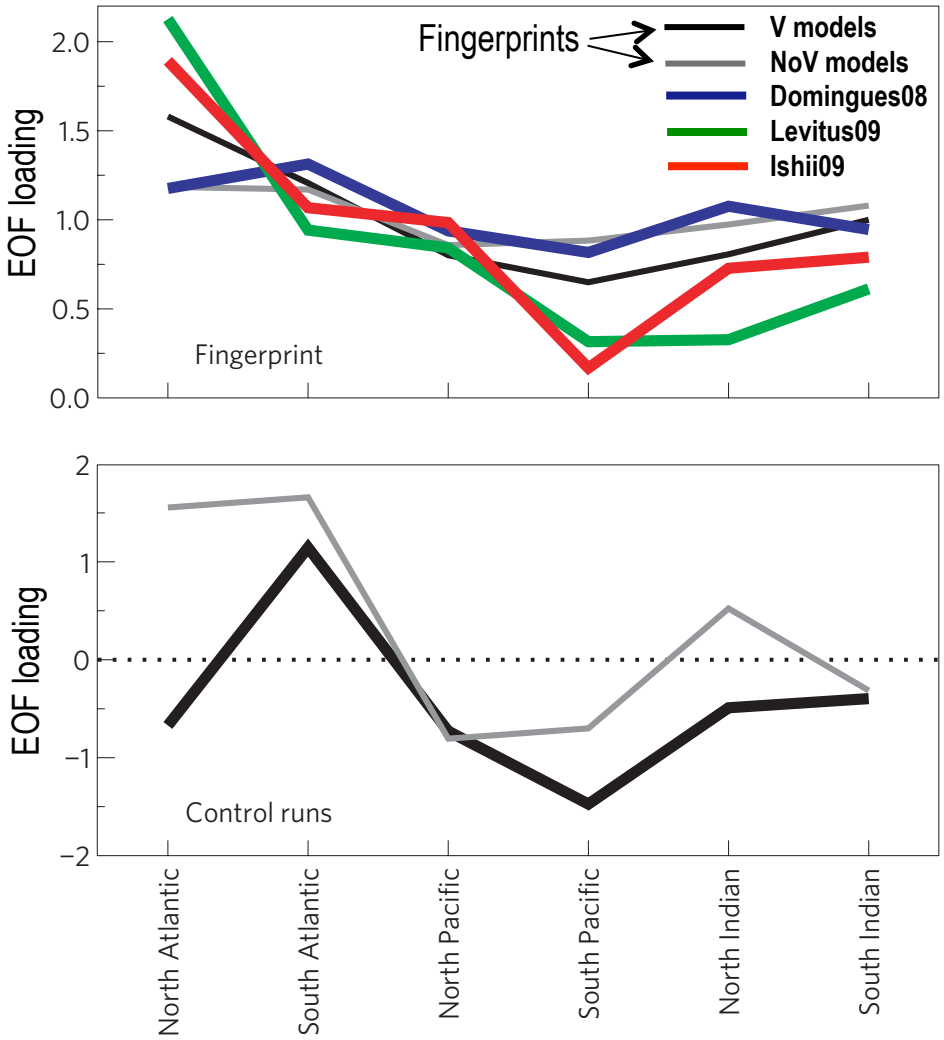
CMIP3 multi-model avg (bars)

Black bars = NoV models
Grey bars = V models
Solid bars = spatially complete
Checkered bars = subsample

- V simulations in better agreement with obs in all basins
- Forcing has greater impact on simulation trends than subsampling
- Subsampled vs Infilled differences are larger for obs (subsampling avoids using data relaxed to climatology)

SS = subsampled
IF = infilled

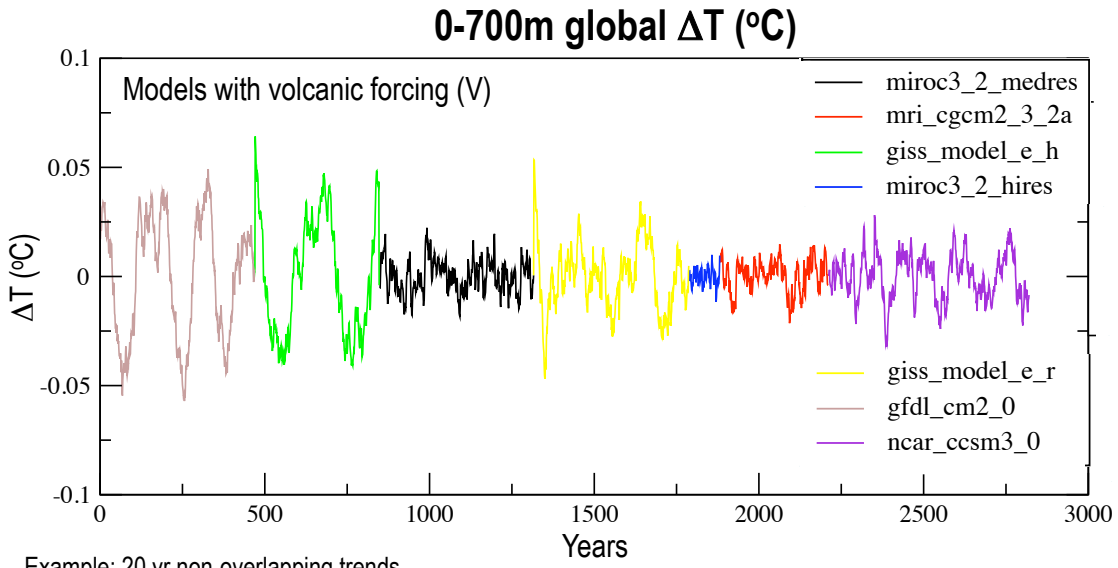
Structure of our fingerprint (and noise estimates)



- V and NoV fingerprints (leading EOF): positive loading in all basins
- Noise does not have the same sign in all basins. Differences between V and NoV due to structural differences in the models (e.g., in physics, resolution, parameterizations)

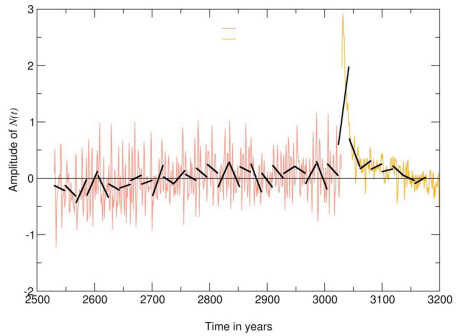
Example shown: spatially complete (not subsampled), quadratic control run drift removal

Multi-model noise estimates (as a function of timescale)

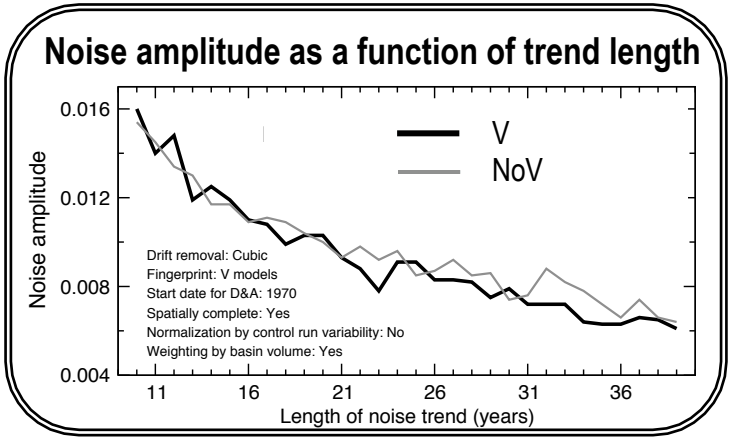


- Pooled model pre-ind control runs
- Structure varies from model to model
- Produced for each basin, then projected onto the V multi-model fingerprint yielding control run pseudo-PCs

Example: 20 yr non-overlapping trends

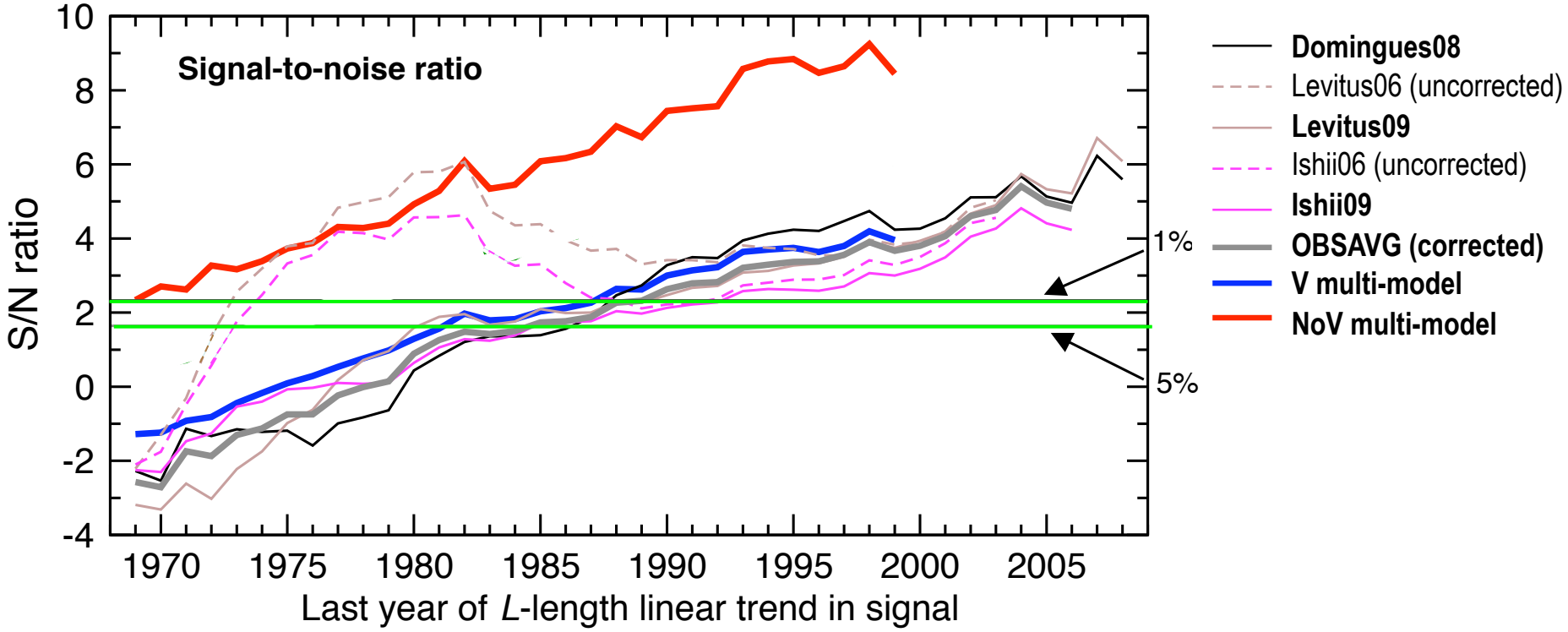


Noise estimate: the S.D. of the sampling distribution of non-overlapping trends, computed at each trend length



Example shown: spatially complete (not subsampled), quadratic control run drift removal

Detection and attribution analysis



This Example:

- Spatially complete (infilled),
- V model fingerprint
- 1960 start date
- Cubic drift removal

- V multi-model and OBSAVG results very similar
- *Detection time* between 1987-1993
- S/N since 2002 > 4

D&A sensitivity tests

Using three biased corrected observational estimates, and multiple models that include the effects of volcanic eruptions, we obtain S/N estimates > 4 (detection at 1% significance threshold) for ~30-40 year timescales. This result is robust to:

- Selection of observational estimate
- Use of infilled or sub-sampled data
- Simulation drift removal technique
- Fingerprint estimate
- Choice of start date (1960 or 1970)

Could our multi-model noise estimates artificially inflate our S/N results?

- **Our ability to test the longer timescale variability of simulated ΔT is limited by the historical record of measurements**

- We compute non-overlapping linear trends on 5 and 10 year time scales, and

- Pool basin results to compute a space-time standard deviation

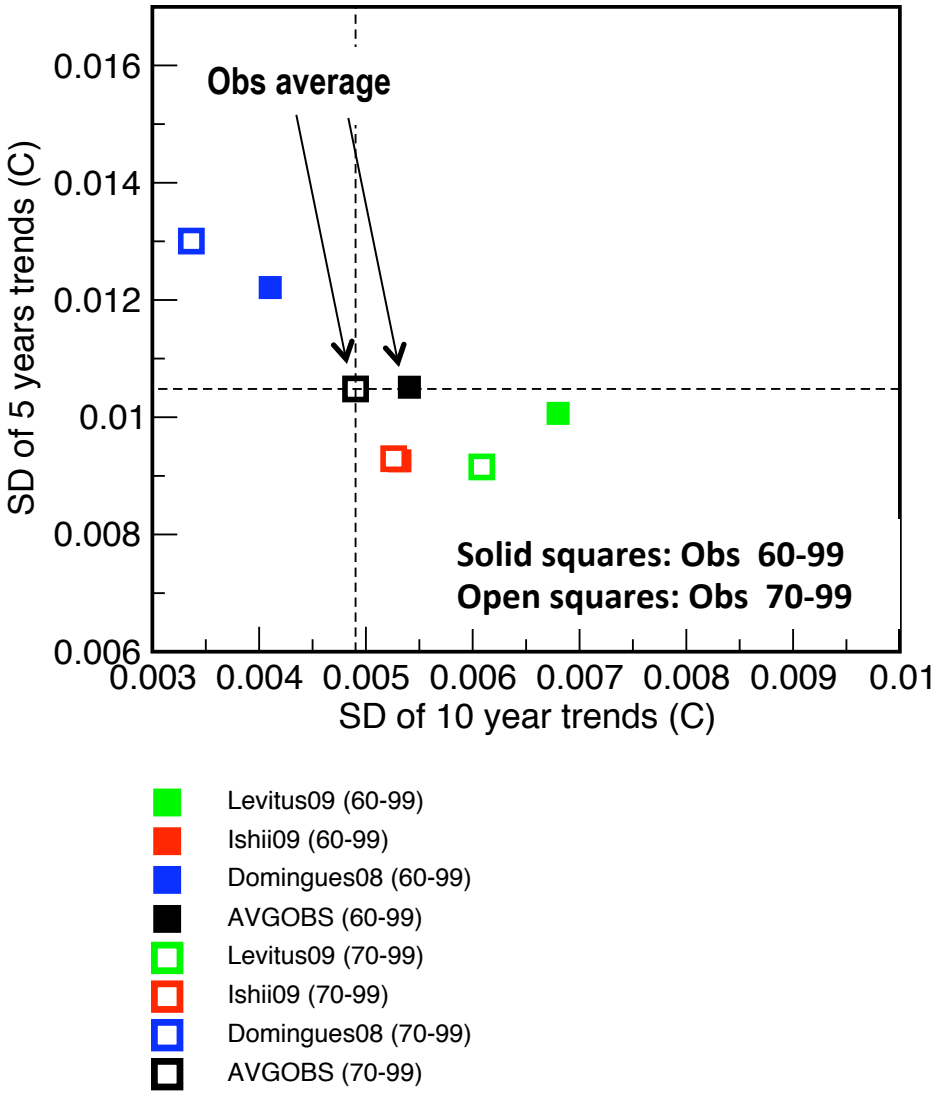
- This variability metric is computed for observations and simulations, for both the infilled and subsampled case

Example: for the 10 year time scale, there are:

- four non-overlapping trends (1960-1969, 1970-1979, 1980-1989 and 1990-1999)
- seven basins (including global)
- yielding a sample size of 28

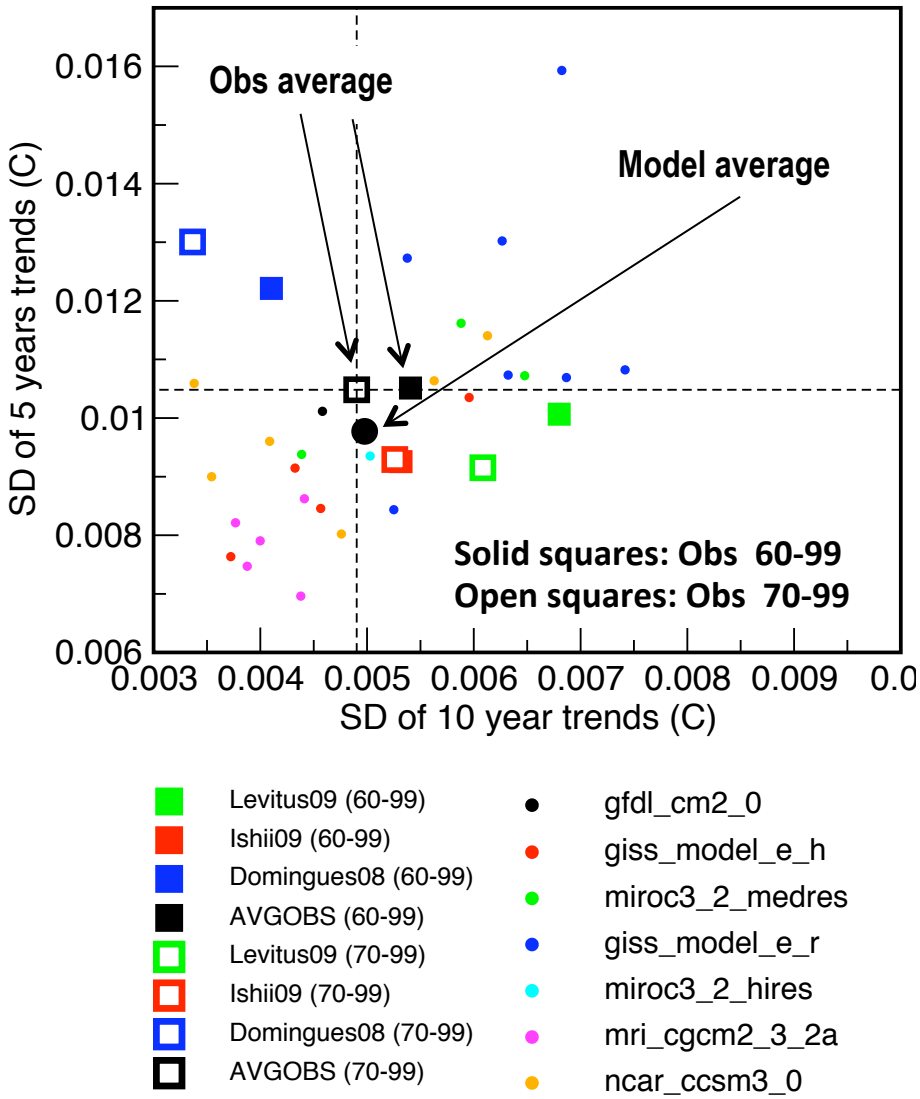
Space-time variability
"Infilled" case

- Obs 10 yr timescale variability is higher when 1960s data is included



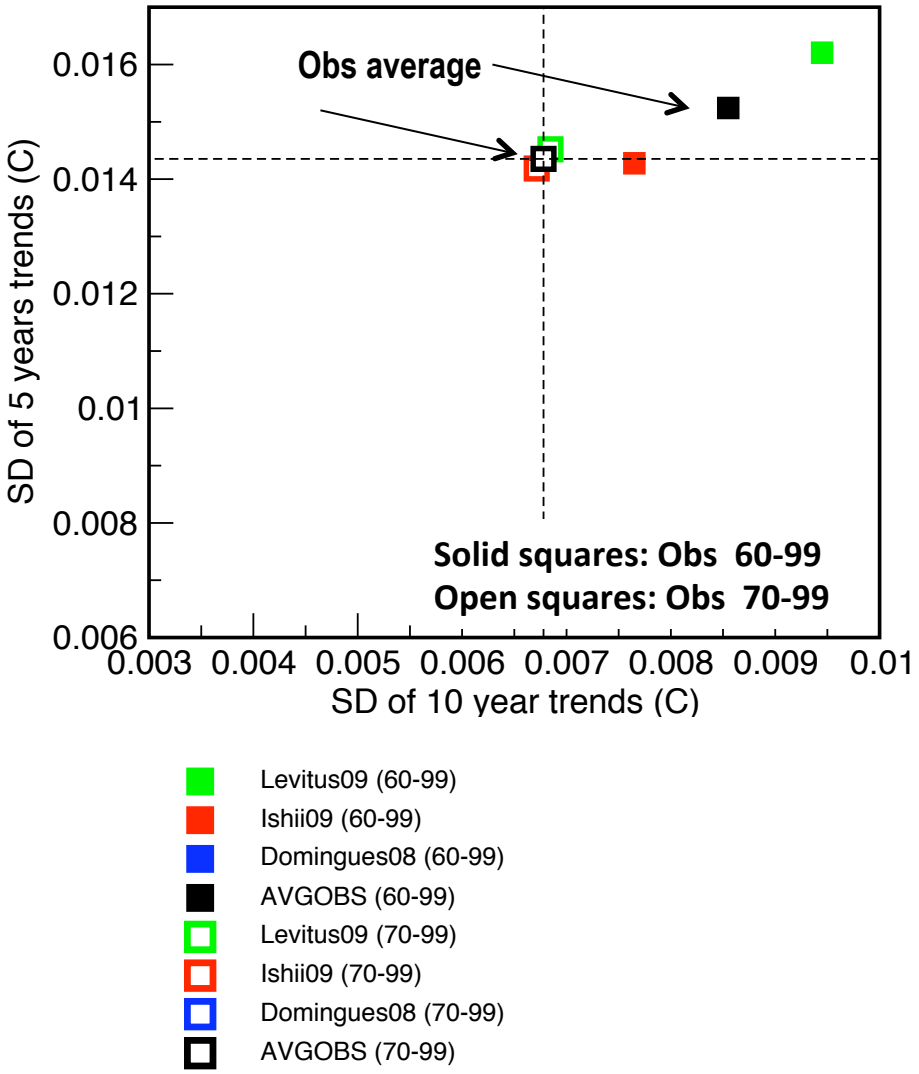
Space-time variability
"Infilled" case

- Obs estimates sensitive to inclusion of 1960s data
- Average model and obs results are indistinguishable at 10yrs



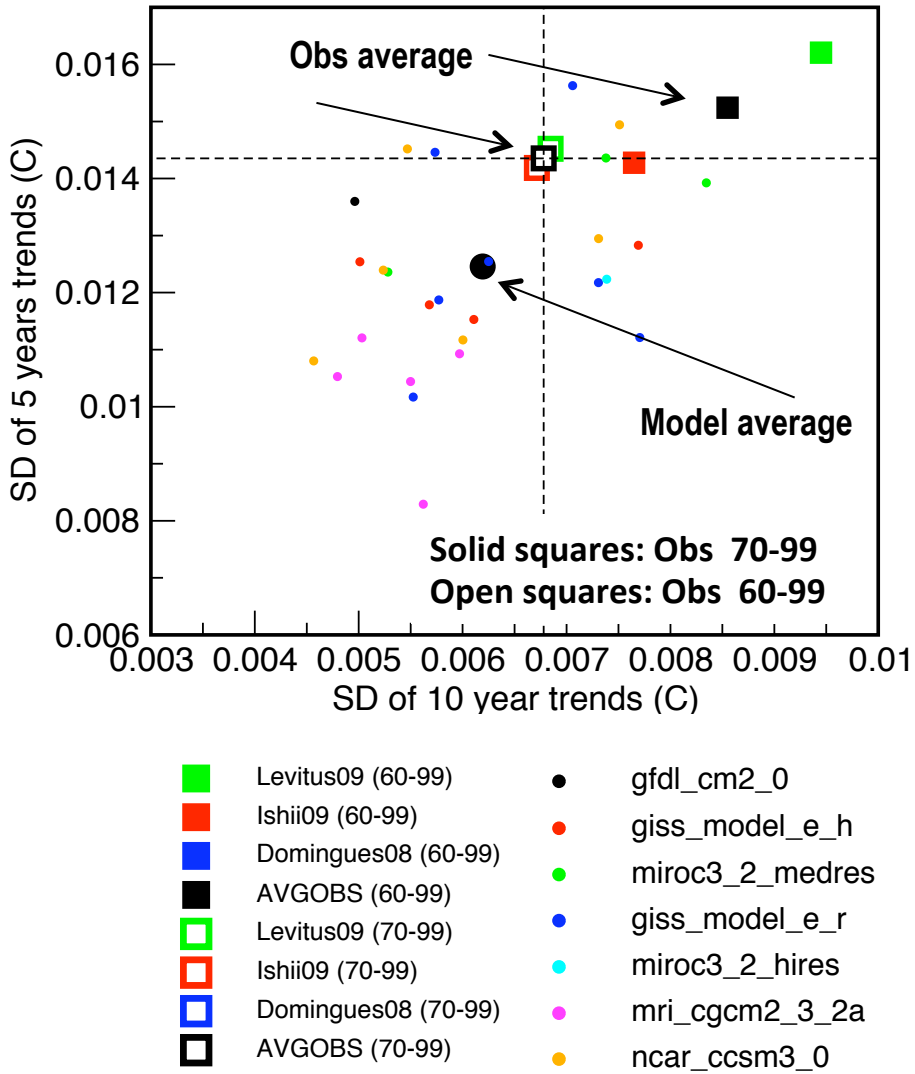
Space-time variability
"Subsampled" case

- Obs estimates very sensitive to inclusion of 1960s data
- Inconsistency evident when 1960 are included (for subsampled case the two estimates are expected to be very similar since they used the same input data source)



Space-time variability
"Subsampled" case

- Obs estimates very sensitive to inclusion of 1960s data
- Limited evidence suggests that the CMIP3 models may underestimate 10 yr basin-scale variability ~10-25%



Summary and conclusions

Estimating longer time scale variability

When subsampling model data to be consistent with historical measurements, we find that the CMIP3 models may underestimate observed 10yr space-time variability by ~10-25%.

Its impact

However, to refute the significance of our D&A results at the 1% level, models would have to underestimate observed variability by more than a factor of two. We find no evidence of such an underestimate.

Ocean warming D & A conclusions

The evolution of the observed basin-scale warming pattern is consistent with our estimated fingerprint (i.e., multi-model response to anthropogenic forcing), but is inconsistent with estimates of longer-time scale variability. These conclusions are robust to a variety of analysis choices and both observational and model uncertainties.

Future work: Ocean warming D&A

- Extend "model quality" evaluation with CMIP5 simulations, focusing on possible deficiencies in simulated variability

- Further explore uncertainties associated with observations, continuing collaboration with leading observational teams:
  - Argo era and CMIP5 adds 10 critical years to our record
  - Challenges "stitching" both OBS and model data:
    - historical XBT and ARGO era data
    - CMIP5 historical and 5 years of RCP scenarios

Alternate approaches

- Revisit space-time D&A methods with CMIP5 (collaboration with Pierce/Barnett, SIO)

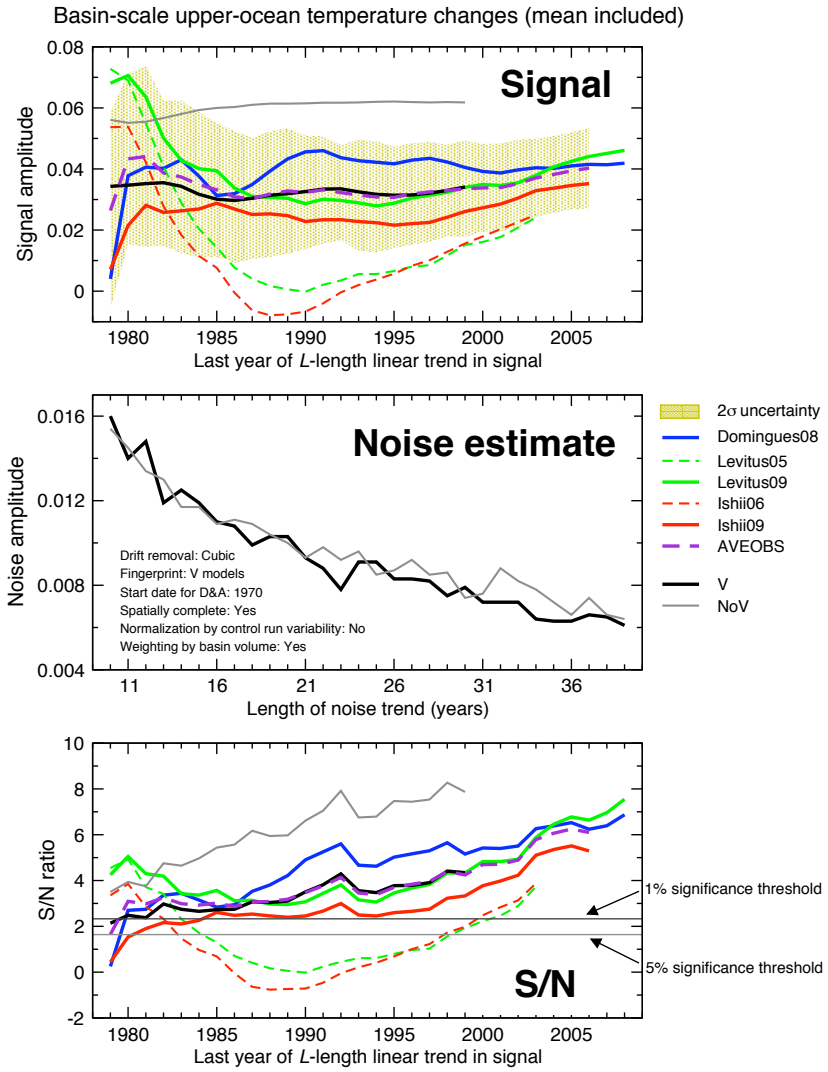
- Sub-basin scale analysis (isothermal approach)

SUPPLEMENTAL SLIDES

Detection and attribution analysis

Example: Spatially complete (infilled), cubic drift removal, V model fingerprint

Signal Trends, Noise Trends, and S/N Ratio: 1970 Start Date



Signal

- NoV unrealistically large
- Uncorrected obs are unusual
- V and AVEOBS very similar

Noise

- V and noV broadly consistent decrease with increasing time scales

S/N

- S/N since 2000 > 4
- V and AVEOBS very similar
- Most 'detection times' are in early 1980s